

**PREDICTION OF RUPTURE ANALYSIS AND
HEMODYNAMIC FACTORS ON ABDOMINAL AORTIC
ANEURYSM FOR NORMAL AND HIGH BLOOD
PRESSURE SUBJECTS**

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**FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR**

2012

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**RESEARCH REPORT SUBMITTED IN PARTIAL
FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF
ENGINEERING (BIOMEDICAL)**

**FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR**

2012

UNIVERSITI MALAYA

ORIGINAL LITERARY WORK DECLARATION

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Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"):

Prediction of Rupture Analysis and Hemodynamic Factors on Abdominal Aortic Aneurysm for Normal and High Blood Pressure Subjects

Field of Study: **Biomechanics**

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Abstract

Abdominal aortic aneurysm (AAA) is a bulging and widening of the blood vessel due the weakening of aortic wall which may lead to rupture of aneurysm if it is not treated. Normally, the treatment of AAA is considered if the maximal diameter exceeds around 5-6cm. The increasing of the bulge is proportional to potential of aneurysm rupture. The ultimate goal of the study is to investigate the hemodynamic factors at the AAA region in terms of velocity, pressure and wall shear stress for normal and high blood pressure both at resting and exercise condition. The aneurysm model used in this study has been reconstructed from computed tomography scan (CT-scan). In order to simulate the behaviour of the hemodynamic factors, Computational fluid dynamic (CFD) and finite element analysis (FEA) software is used. The criteria of the flow are Newtonian and pulsatile flow. These criteria are applied in this simulation for both normal and high blood pressure at exercise and resting condition. Based on the results, the pressure distribution of the aneurysm is influenced by flow behaviour where it was found that pressure inside the aneurysm is proportional to blood velocity. On the other hand, wall shear stress (WSS) shows increment of stress in the early stage and reached its peak at the late stage of the periodic time. The hemodynamic factors considerably influence the expansion of aneurysm for both high and normal blood pressure. However, in every case experimented, hypertensive blood pressure during exercise exhibited greater hemodynamic effect in the aneurysm region due to active blood flow.

Abstrak

Abdominal aortic aneurysm (AAA) adalah pembengkakan dan pembesaran salur darah disebabkan kelemahan dinding aneurism yang cenderung untuk pecah jika tidak dirawat. Kebiasaannya, rawatan bagi AAA akan diberi bagi aneurysm yang mencapai diameter 5-6 cm. Kenaikan pembengkakan adalah berkadar terus dengan potensi aneurism untuk pecah. Matlamat utama kajian ini adalah untuk mengkaji faktor hemodinamik pada AAA dari segi halaju, tekanan dan tegangan terikan pada dinding aneurism bagi tekanan normal dan tekanan darah tinggi termasuk pada keadaan rehat dan bersenam. Model aneurism yang digunakan berdasarkan model pengimbas *computed tomography* (CT-scan). Perisian *Computational Fluid Dynamic* (CFD) and *Finite Element Analysis* (FEA) digunakan untuk mensimulasi faktor hemodinamik tersebut. Kriteria aliran adalah *Newtonian* dan aliran *pulsatile*. Kriteria ini diaplikasikan dalam simulasi aneurism dalam keadaan rehat dan bersenam bagi tekanan tinggi dan normal. Daripada hasil kajian, pola tekanan dalam aneurism dipengaruhi oleh corak pengaliran darah. Tambahan pula, hasil kajian mendapati tekanan dalam aneurism berkadar terus dengan halaju darah. Bagi *wall shear stress* pula, nilai tekanan meningkat pada kitar awal dan mencapai puncak pada kitar akhir. Faktor hemodinamik sememangnya mempengaruhi pemngembangan aneurism bagi tekanan tinggi dan normal. Namun begitu, bagi setiap simulasi yang dijalankan, tekanan tinggi ketika bersenam menunjukkan kesan hemodinamik yang tinggi pada aneurism oleh kerana pengaliran darah yang aktif.

Publications

The research described in this thesis has led to the following publication and presentation:

Proceeding

1. M. R. Amir Hamzah, I. Taib, M. S. Ramlee and N. A. Kadri. (2012). Rupture Prediction Analysis of Abdominal Aortic Aneurysm due to Hemodynamic Factors in Normal and High Blood Pressure at Rest and During Exercise. Proceedings of the International Federation for Medical and Biological Engineering. World Congress on Medical Physics and Biomedical Engineering, 26-31 May 2012, Beijing, China. ISSN 1680-0737. (Accepted) (*ISI-Cited Proc.*).

Acknowledgements

Thanks to Almighty Allah, the Most Gracious and the Most Merciful, who gave me the knowledge, courage and patience to complete this research. May the peace and blessings of Allah be upon Prophet Muhammad Sallallahu alaihi wasallam.

Further, I would like to express my heartiest gratitude to my supervisor, Dr Nahrizul Adib Kadri, from Faculty of Biomedical Engineering, University Malaya, Kuala Lumpur. His constructive comments, guidance, suggestion and encouragement have contributed to the success of this research. I am thankful for his advice and willingness to share his bright thoughts.

I wish to express my sincere gratitude to my mentor, Iskhizat Taib from University Tun Hussein Onn Malaysia for his teaching and guidance. His contractive ideas and technical support has smoothen my project work. I also acknowledge Faculty of Mechanical Engineering, University Tun Hussein Onn Malaysia, Johor for providing all the instruments and knowledge necessary for my study.

I also would like to convey special acknowledgement to my parents and beloved wife, Norsiken Mohd Ishak for their encouragement and understanding that they have given to me all along the journey of life.

Last but not least, I would like to express my sincere appreciation to the entire individuals who have assisted me directly or indirectly throughout completing this study successfully.

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LIST OF ACRONYMS

AAA	Abdominal Aortic Aneurysm
CFD	Computational Fluid Dynamic
FEA	Finite Element Analysis
HBP	High Blood Pressure
HBPE	High Blood Pressure during Exercise
NBP	Normal Blood Pressure
NBPE	Normal Blood Pressure during Exercise
WSS	Wall Shear Stress

CHAPTER I

INTRODUCTION

1.1 Background of the Study

The aorta is the largest artery in the human body, transporting oxygenized blood. An aortic aneurysm is a local dilation in the aorta of more than 1.5 times the original diameter (Johnston et al., 1991). Although aneurysms can be present in every part of the aorta, the majority of the aortic aneurysms are situated in the abdominal aorta (Figure 1.1), below the level of the renal arteries and above the aortic bifurcation to the common iliac arteries (Crawford and Cohen, 1982). Abdominal aortic aneurysm (AAA) is a localised dilatation (ballooning) of the abdominal aorta exceeding the normal diameter by more than 50 percent, and is the most common form of aortic aneurysm. It occurs whether below the kidneys, but they can also occur above the kidneys.

Most computational work in aneurysms is focusing on blood flow and wall stress analyses which develop from clinical data of aneurysm models. The rupture of an aneurysm occurs mainly due to the diameter, wall thickness and blood pressure inside aneurysm (Yamada et al., 1994). Fluid dynamic simulation has the ability to demonstrate the distribution of the velocity and the pressure of the mathematical model of blood vessel. This method can be applied to study the flow

of the blood and the local pressure elevation at the aneurysm created from the modelling part that has been scanned into software. After that, the flow behaviour around the aneurysm could be simulated in the patient-specific vessel models (Masaaki et al., 2005).

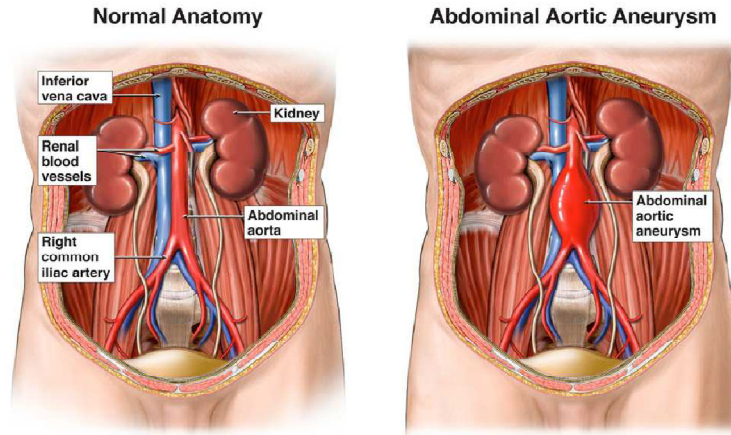


Figure 1.1: Normal aorta and abdominal aortic aneurysm

Source: [http:// www.nucleusinc.com](http://www.nucleusinc.com)

There have been several research efforts to investigate the flow phenomena inside aneurysm using numerical simulations (Paal et al., 2007). The first technique is using artificial models which are supposed to reflect the important geometrical and flow characteristics of the aneurysm and secondly, simulations on real models derived from medical imaging scanner techniques. In the case of artificial models, the researcher has complete freedom in preparing the geometry and the numerical mesh.

Because of the relative simplicity, regularity and controllability of the geometry, the mesh has usually results a good quality. Examples for such artificial

geometries can be referred to Egelhoff et al., (1999) for the study of abdominal aneurysms and abdominal aortic branches study conducted by Shipkowitz et al., (2000) and Paal et al., (2007). These studies are conducted to develop a technique that is able to simulate blood flow inside aneurysms in order to study the effect of the flow behaviour that could cause rupture of aneurysm.

It is generally accepted that geometry (shape and size) of the blood vessel influenced the blood flow behaviour in the aneurysm. Understanding the blood patterns passing through the aneurysm and physically analyze the progression of aneurysms vessel wall will benefit and support the surgeon to understand aneurysm growth, prepare treatment and predict the risk of its re-growth after treatment.

Pulsatile flow characteristics in AAA have been considered by many researchers in which the flow pattern is different from that of steady flow. The hemodynamic stresses are higher in pulsatile flow rather than in steady flow as illustrated in the pulsatile flow behaviour which is significant to determine the development of the atherosclerosis and thrombus formation in AAAs. Peattie et al., (2004) has simulated the resting time in vivo for fusiform model for the pulsatile flow to analyze the flow behaviour and shear stress distribution at aneurysm wall. As a result, the flow behaviour inside the aneurysm becomes unstable proportional to the increment of the bulge aneurysm size. Egelhoff et al., (1999) has studied both numerically and experimentally, on the effect of the pulsatile flow on the hemodynamic state which may influence the growth of the aneurysm under resting and exercise time. Taylor et al., (1994) have studied the numerical modeling for physiological lumbar curvature under resting and exercise condition on rigid

aneurysm wall. The lower extremity exercise may limit the progression of the AAA and resistive hemodynamic condition.

One way to measure the flow behaviour is by determining the velocity bandwidth inside the aneurysm. Velocity bandwidth is defined as the difference between the maximum and the minimum velocity values. High velocity bandwidth may indicate presence of vortex or vortices and high velocity bandwidth also shows active flow behaviour inside the aneurysm.

1.2 Problem Statement

The expansion of the aneurysm segment eventually increase the risk of the aneurysm rupture (Lederle et al., 2002) although, rupture could occur in a small aneurysm (Darling et al., 1977). The aneurysm rupture is a major complication at the disease vessel especially in AAA which lead to 90 percent of the patients died (Elger et al., 1995). Thus, early detection of the aneurysm rupture is crucial to overcome this problem by using the computational modeling techniques which include the fluid, pressure and wall interaction for better prediction. Hence, the study will improve the simulation techniques and facilitate the healthcare professionals to make early and better prediction of aneurysm rupture and also directly improve the decision-making either for or against surgery.

1.3 Objectives

The main objective of this study is to model AAA in three dimensions (3D) based on CT-scan data. In addition, the study will also focus on investigating the hemodynamic factors around the AAA region in terms of velocity, pressure and wall shear stress for normal and high blood pressure both at rest and during exercise.

1.4 Hypothesis

The prediction of AAA rupture analysis is highly dependable on the hemodynamic factor, namely flow behaviour, pressure and wall shear stress. The interaction of these factors is strongly believed to affect hypertensive patient over normal blood patient as they exhibit active blood flow and greater pressure. In addition, exercise condition which showed high blood velocity is reasonable to contribute rapid flow pattern compare to resting condition. Moreover, active flow will lead to rapid changes in aneurysm region that can lead to aneurysm expansion and particular areas that is highly risk to rupture.

1.5 Scope of Study

The research study is based on the following scopes:

1. The simulation is focused on virtual fusiform Abdominal Aortic Aneurysm referred directly from clinical CT-scan data.
2. The flow disturbance inside the abdominal aortic aneurysm region is analysed using numerical approach where Computational Fluid Dynamic (CFD) and Finite Element Analysis (FEA) are used.
3. The analysis will focus on the flow pattern, pressure distribution and wall shear stress for both high blood and normal blood pressure.

CHAPTER II

LITERATURE REVIEW

2.1 Abdominal Aortic Aneurysm

Abdominal aortic aneurysm (AAA) contributes significantly to the disease burden of the elderly population, with as much as 10% of the population over the age 65 potential to get an aneurysm (Khanafer et al., 2007). Several experimental and numerical studies of blood flow at constant flow rates through aneurysms are found in the literature. Flow visualisation studies for steady flow in in-vitro spherical models of aneurysms resulted in the determination of streamline patterns inside the bulge models. These results show the formation of a jet of fluid passing through the aneurysm, surrounded by a region of recirculating flow. Stehbens observed boundary layer separation and reattachment in flow visualisation experiments with glass models of different aneurysm shapes and sizes. An improvement in experimental modelling is made and regions of stagnant and reversed flow in asymmetric casting resin models of aneurysms is observed (Drexler and Hoffman, 1985).

Numerical and experimental studies of steady flow demonstrate the effect of flow patterns in the distribution of pressure and shear stresses at the wall. The steady flow numerical simulations show the existence of two symmetric vortices in

three-dimensional asymmetric computational models (Taylor and Yamaguchi, 1994). In other study, wall pressure inside the aneurysm model reaches a maximum at the centre, while turbulence increases wall shear stresses by an order of magnitude at the distal edge of the bulge (Peattie et al., 1994). Correlation between steady blood flow dynamics and rates of platelet deposition proved the existence of a monotonic increase of platelet aggregation at the aneurysm wall, until reaching a maximum at the distal edge

The focal dilation of blood vessel is located between renal arteries and iliac bifurcation which is illustrated in Figure 2.1. AAA can be defined when the diameter of aortic wall expand at least 1.5 times of the normal diameter of aorta at renal arteries. Newman et al., (2001) reported that approximately 8.8 percent of the prevalence of the AAA affects the people above 65 years old and men are slightly more affected rather than woman in ratio 4:1. In the clinical practices, when the diameter of aneurysm exceeds 5 to 6 cm, surgical treatment of AAA is considered.

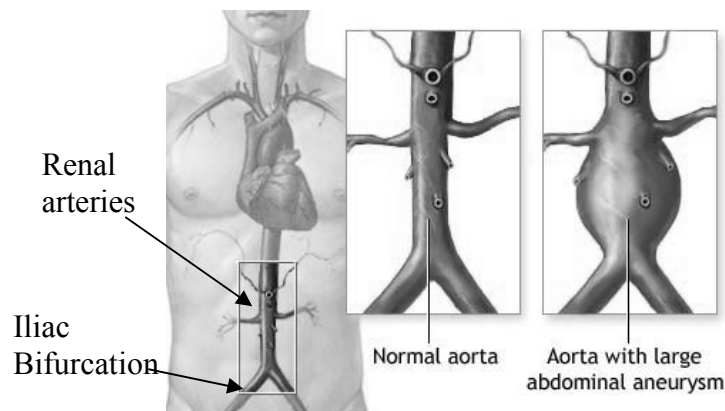


Figure 2.1: Comparison between normal aorta and aorta with large aneurysm.

(Source: <http://graphics8.nytimes.com/images/2007/08/01/health/adam/18072.jpg>)

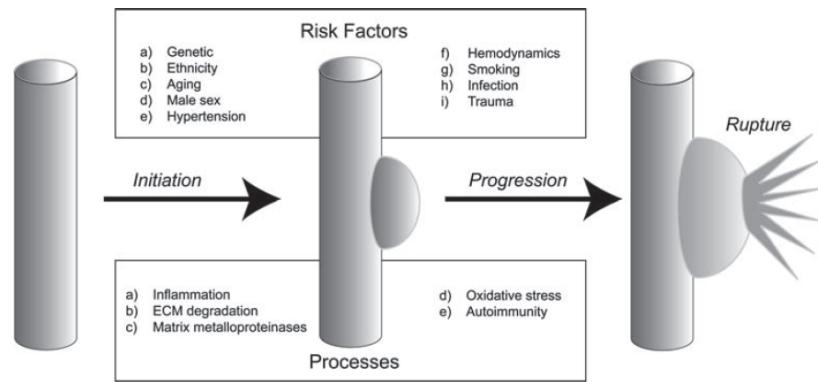


Figure 2.2: The figure shows how abdominal aortic aneurysm (AAA) relates to risk factors and processes involving in AAA formation, growth, and rupture.

2.2 Types of Aneurysm

Aneurysm can occur in any blood vessel. Currently there are four types of aneurysm is a known fact. Figures below shows the types of aneurysm but in this study, only abdominal aortic aneurysm (AAA) is considered.

2.2.1 Abdominal Aortic Aneurysm (AAA)

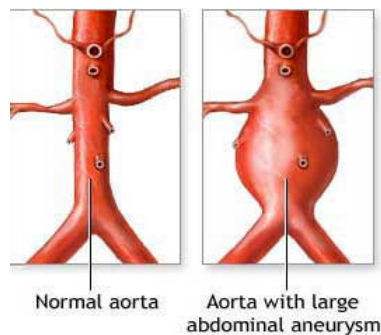


Figure 2.3: Abdominal aortic aneurysm.

(Source:<http://heartstrong.files.wordpress.com/2010/08/abdominal-aortic-aneurysm-320.jpg>)

Abdominal aortic aneurysm is a localised dilatation (ballooning) of the abdominal aorta exceeding the normal diameter by more than 50 percent, and is the most common form of aortic aneurysm.

2.2.2 Thoracic aortic aneurysm

The aorta is the largest artery in the body and is the blood vessel that carries oxygen-rich blood away from the heart to all parts of the body. The section of the aorta that runs through the chest is called the thoracic aorta and, as the aorta moves down through the abdomen it is called the abdominal aorta.

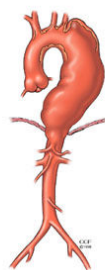


Figure 2.4: Thoracic aortic aneurysm.

(Source:http://my.clevelandclinic.org/PublishingImages/heart/ao_aneurysm1.jpg)

2.2.3 Dissecting aneurysm

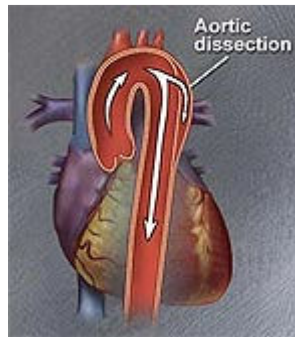


Figure 2.5: Dissecting aneurysm.

(Source: <http://www.mayoclinic.org/images/dissectinganeurysm-bdy.jpg>)

Aortic dissection, also called dissecting aneurysm, is relatively uncommon. It is a serious condition in which a tear develops in the inner layer of the aorta, the large blood vessel branching off the heart. Blood surges through this tear into the middle layer of the aorta, causing the inner and middle layers to separate (dissect). If the blood-filled channel ruptures through the outside aortic wall, aortic dissection is usually fatal.

2.2.4 Brain aneurysm

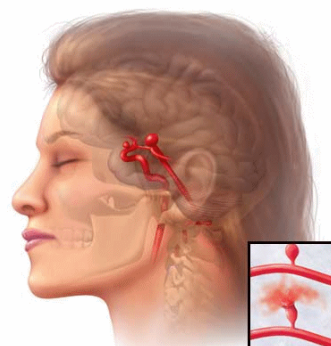


Figure 2.6: Brain aneurysm.

(Source: <http://www.mayoclinic.com/health/brain-aneurysm/DS00582>)

A brain aneurysm is a bulge or ballooning in a blood vessel in the brain. It often looks like a berry hanging on a stem. As the blood vessel weakens, it begins to bulge out like a balloon. Often, as an aneurysm develops, it forms a neck with an associated dome, or balloon like structure.

2.3 Types of Abdominal Aortic Aneurysm

Figure 2.7 shows the general shapes of aneurysm. There are three general types or shapes. Saccular aneurysms are those with a saccular outpouching and are the least common form of cerebral aneurysm. Berry aneurysms are saccular aneurysms with necks or stems resembling a berry. A fusiform aneurysm is a type of aneurysm characterised by a spindle-like shape when viewed in cross-section. It can be a cause for concern, depending on where in the body it is located, and in some cases emergency surgery may be required to correct it before it ruptures. A pseudoaneurysm sometimes called a false aneurysm can happen after an artery or heart chamber is injured. If an injury to an artery causes blood to leak and pool outside the injured artery's wall, a pseudoaneurysm can form. In a true aneurysm, blood collects inside the artery wall.

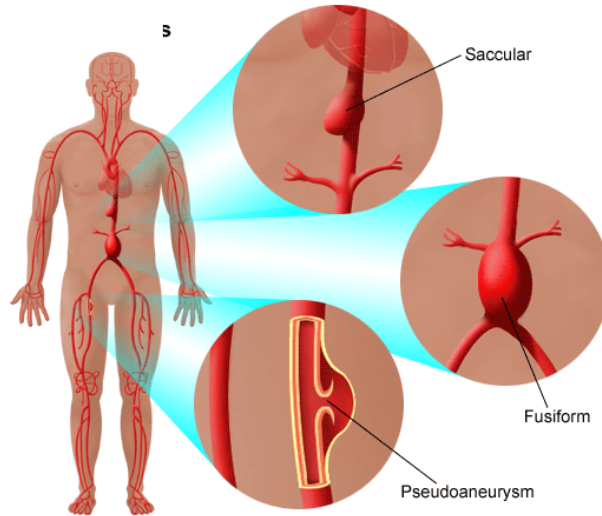


Figure 2.7: Types/shapes of Abdominal Aortic Aneurysm.

(Source:<http://www.healthpress.us/wp-content/uploads/2010/12/types-of-aneurysms.gif>)

2.4 Parameter Assumption and Blood Properties

There were several assumptions imposed on the model in this study. Table 2.1 summarizes the parameter assumptions for previous and present study. This table shows the exercise condition, resting condition, pulsatile flow, non pulsatile flow, Newtonian and Non Newtonian. The effect of Normal Blood Pressure (NBP) and High Blood Pressure (HBP) toward the aneurysm was studied in order to identify the significant of the NBP and HBP to drive the AAA development. Additional to the NBP and HBP flow conditions, this study also adds the physiological realistic exercise flow condition to investigate the effect of the combinations of the flow conditions. Resting condition is used as the basis of the comparisons. Researchers (Elger et al., 1995; Finol et al., 2001; Fukushima, 1989

and Khanafer, 2006) that have considered to use pulsatile flow in rigid AAA wall revealed that the pulsatile flow is much differ from those the steady flow which illustrated that the importance of the pulsatile flow in AAA development especially in arteriosclerosis and thrombosis. Pedersen E. (1993) studied a quantitative velocity data for realistic abdominal aorta in two dimensional under resting and exercise condition.

Hirabayashi (2006) reported that the blood exhibit as non-Newtonian behaviour. Other researchers reported that Newtonian liquid is sufficient for the case of large blood vessel. In this study, Newtonian condition is used due to the fact that the artery is large enough for the effect of non-Newtonian to be significant. Khanafer (2006) examined that there is no significant data had confirmed the difference for both non-Newtonian and Newtonian fluid which the researcher found that the non-Newtonian effect is minimal in arterial flow pattern. The Newtonian blood properties can be assumed; blood density is 1050 kg/m^3 , Newtonian reference viscosity is 0.00345 N.s/m^2 , specific heat (Cp) is 4182 J/(kg*K) , Dynamic viscosity is 0.012171 Pa*s .

Table 2.1: Parameter assumptions of previous and present study.

No	Authors	Methods	Details	Parameter Assumptions					
				Exercise Condition	Resting Condition	Pulsatile	Non Pulsatile	Newtonian	Non Newtonian
1	K.M.Kanafer (2007)	Experiment	Study examines the influence of pulsatile, turbulent,non-Newtonian flow on fluid shear stresses and pressure changes under rest and exercise conditions.	✓	✓	✓			✓
2	R.A Jamison (2007)	Numerical	Predict the conditions under which an axisymmetric aneurysmal flow is unstable to non-axisymmetric instabilities.	✓		✓		✓	
3	R. Budwig (1993)	Experiment/ Numerical	Determine overall features of the flow, the stresses on the aneurysm walls in laminar flow, and characteristic of turbulent flow		✓		✓		✓
4	Valerie Deplano (2006)	Experiment	To determine complementary criteria to existing morphological criteria, which are not reliable but are used to justify surgical intervention to treat abdominal aortic aneurysm (AAA).	✓	✓	✓		✓	
5	C.J Egelhoff (1999)	Experiment/ Numerical	Understand the hemodynamic that may contribute to growth of an AAA.	✓	✓	✓		✓	
6	Present Study	Numerical	Prediction of rupture analysis of hemodynamic factors on AAA for normal and high blood pressure during resting and exercise condition.	✓	✓	✓		✓	

CHAPTER III

METHODOLOGY

3.1 Introduction

A numerical investigation is to be carried out to obtain validated numerical prediction of incompressible flow homogeneous, pulsatile blood pressure, velocity distribution, pressure distribution around fusiform aneurysm region. The present study is carried out to analyse the cases of different condition which is High Blood Pressure in exercise and resting condition. The other condition is Normal Blood Pressure in exercise and resting condition.

In order to replicate the model of actual aneurysm, a CT-Scan file is obtained and MIMICS software is used through slice by slice of 240 times and a total figure of aneurysm can be constructed as shown in Figure 3.1 and Figure 3.2. To smoothen the surface of the aneurysm, a 3D modelling software is used which is AMIRA. The benefit of this software is that it can be used to reduce or create mesh and smoothen surface as shown in Figure 3.3 and Figure 3.4.

Computational Fluid Dynamics (CFD) software provides many benefits to its users such as realizable savings in time and cost for engineering design obtain flow information in regions that would be difficult to test experimentally, simulate real flow conditions, conduct large parametric tests on new designs in a short time

and enhance visualisation of complex flow phenomena. The advantages of CFD will help researchers to find the most optimum results.

Meanwhile in Finite Element Method Software, the data from patient for normal and blood pressure is used in boundary condition. In this software the expansion of Abdominal Aortic can be simulated. With the use of CT scan data, the geometry of the aneurysm can be accurately determined and incorporated into a three-dimensional finite-element analysis. CT dataset allows accurate recreation of the aneurysm geometry. Aneurysm surface has captured from CT slices.

A large deformation analysis is performs using ABAQUS commercial code based on the finite element method. In particular, the ABAQUS program is used in the classical displacement formulation. ABAQUS finite element software was employed in this study because it allows one to used contact analysis using linear tetrahedral elements. By using contact analysis, relative motion the can be obtained explicitly and the resulting shear stresses can also be found. Frictional contact was prescribed at the aneurysm interface by means of face-to-face contact elements. AMIRA finite element software is used for the construction of 3D model of femur bone was done using AMIRA software.

3.2 Model Construction using MIMICS and AMIRA

Medical software such as Materialise's Interactive Medical Image Control System (MIMICS) and AMIRA are widely used among doctors that study the internal parts of human body. These software enables doctor to study any problem and defect which occurred inside human organ. It is also most helpful model

construction software especially among mechanical engineer that is related with bio-mechanical. MIMICS linking scanner data such as CT, MRI, Technical Scanner and STL format for finite element analysis. MIMICS is an image processing software with 3D visualisation function that can be interface with all scanner format. Additional module provides interface towards rapid prototyping which use STL format or direct layer support. As such, in imitate medical field can be used for diagnostic purpose, operational planning or training. An interface is very flexible for rapid prototyping systems including to model distinctive segmentation object.

AMIRA is a 3D visualisation data, analysis and system modeling. It is used to visualize for scientific data set from various application area namely medical, biological, biochemical and biomedical.

AMIRA is powerful and platform software with various appearances to reflect, manipulate, and to understand biological sciences and biomedical data that comes from all source type and method. Widely used as 3D visualisation tool in microscope and biomed research, AMIRA has become a product with more functions and more sophisticated, deliver visualisation that is strong and has analysis potential in all visualisation and biomedical field. Overview of aneurysm modeling procedure using both MIMICS and AMIRA software is illustrated in Figure 3.5.

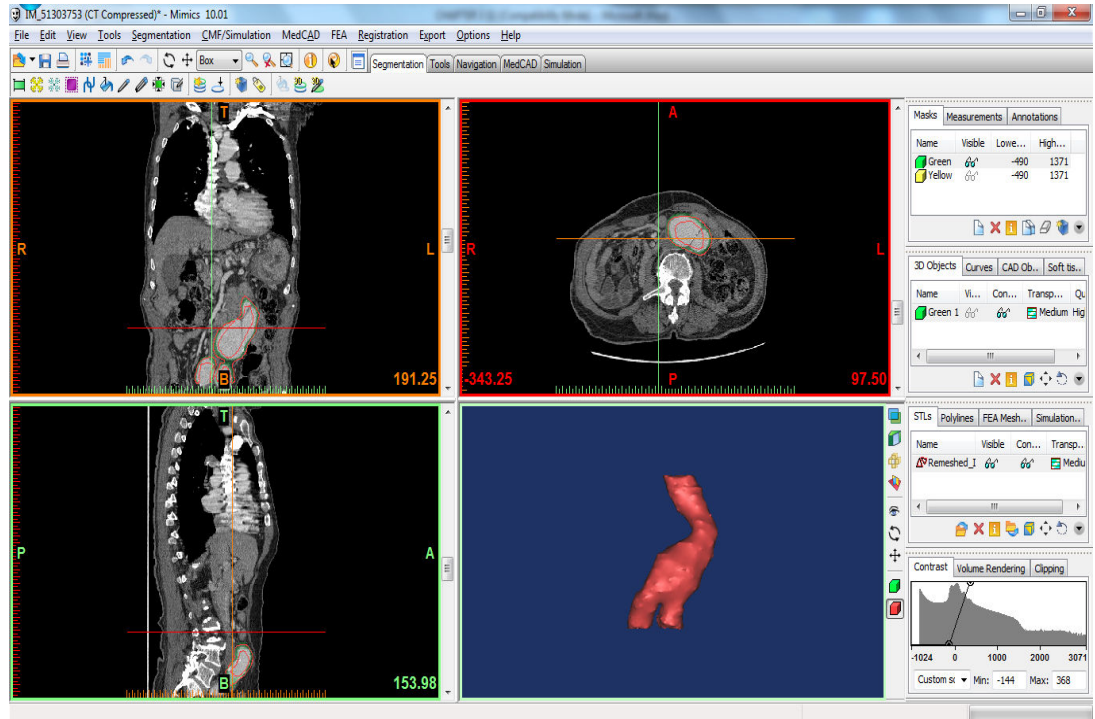


Figure 3.1: Screenshot of aneurysm modeled in MIMICS from CT scan data through slice by slice procedure.

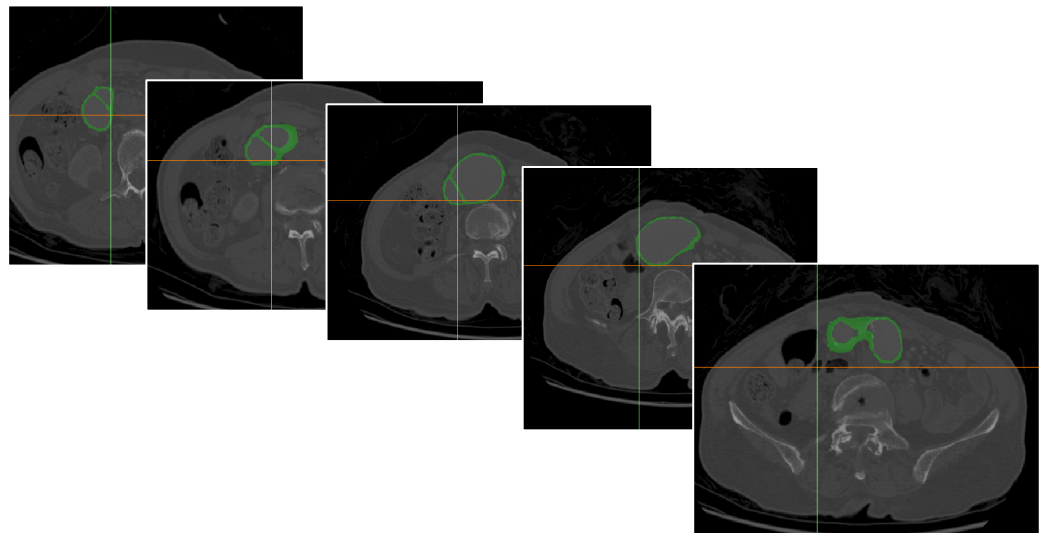


Figure 3.2 The aneurysm model is discovered by deleting the important part slice by slice.

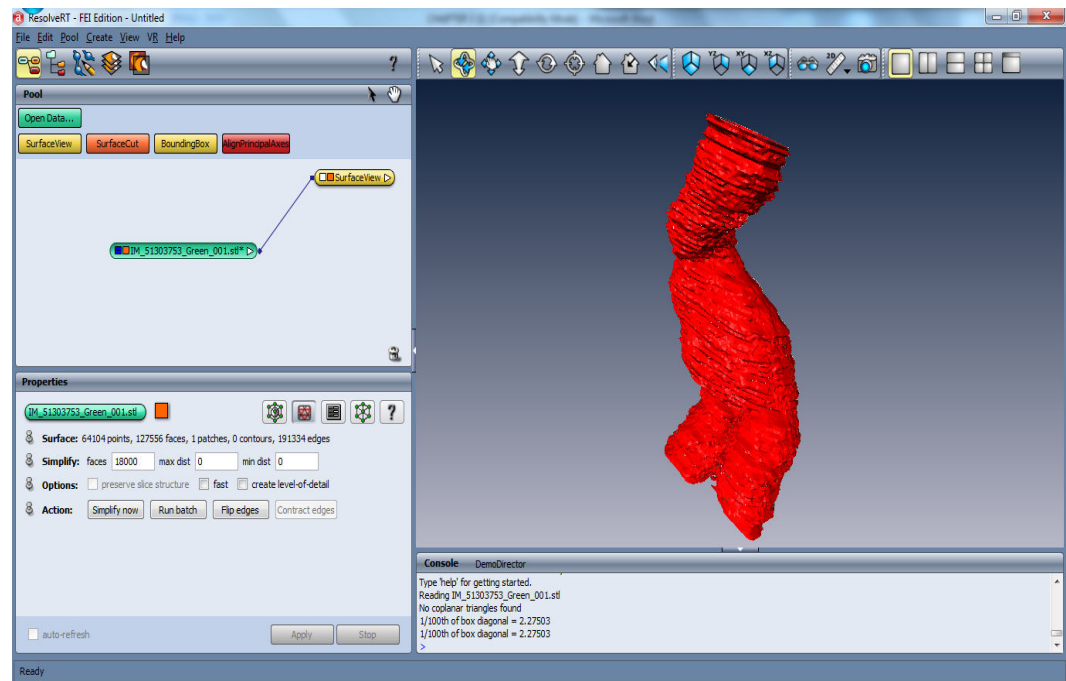


Figure 3.3: Screenshot of constructed aneurysm using AMIRA following MIMICS constructed model.

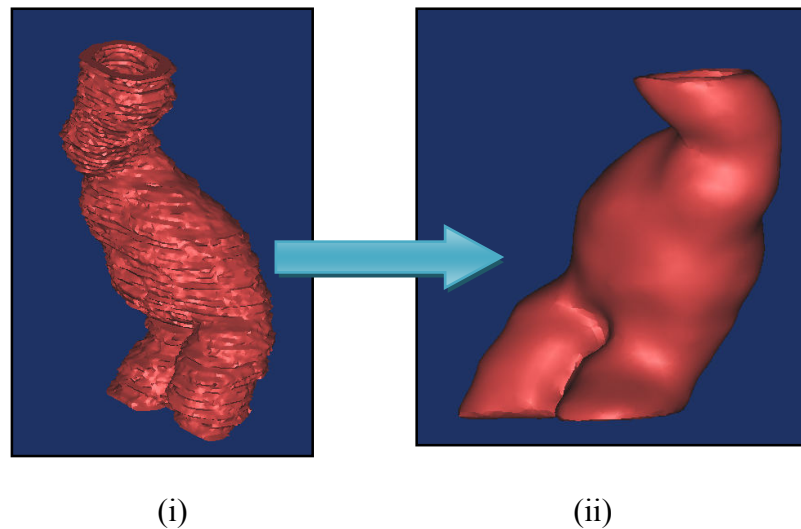


Figure 3.4: Model before (i) and after (ii) smoothen process using AMIRA.

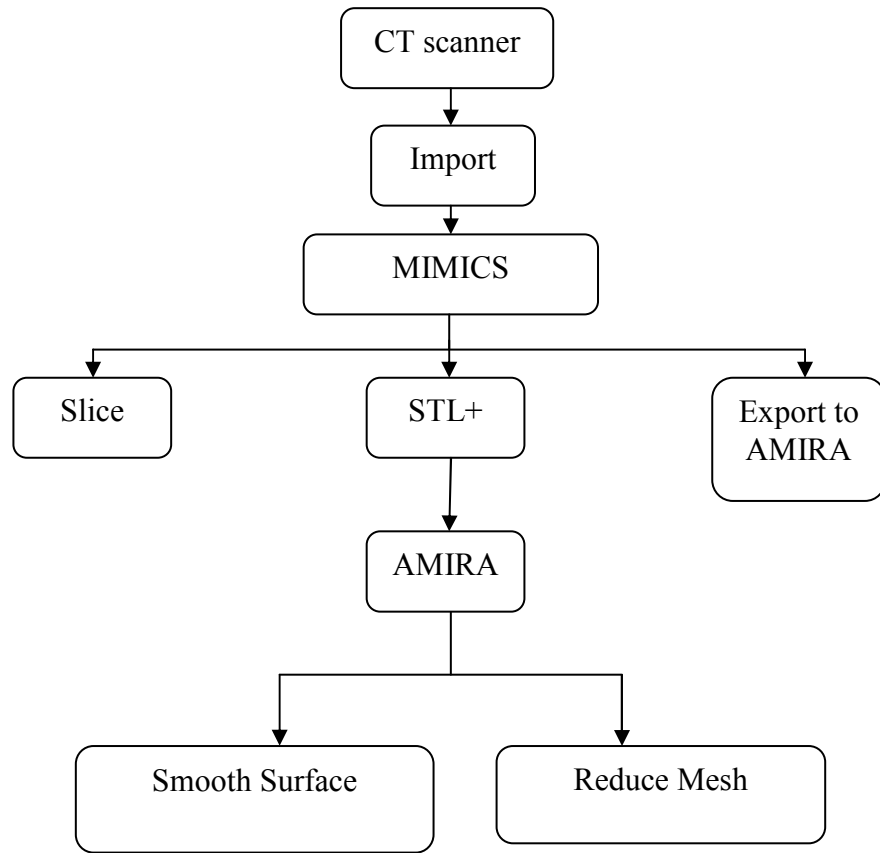


Figure 3.5: Overview of aneurysm modelling procedure using MIMICS and AMIRA.

3.3 Abdominal Aortic Aneurysm Model

Most computational work in aneurysm focused on blood flow and wall stress analysis which is obtained from clinical data. The rupture of an aneurysm occurs mainly due to the diameter, wall thickness and blood pressure inside aneurysm (Yamada et al., 1994) but the actual cause of the rupture is actually not yet fully understood. In this simulation, a model based on actual AAA is constructed as shown in Figure 3.6 whilst its geometry specification is shown in Table 3.1.

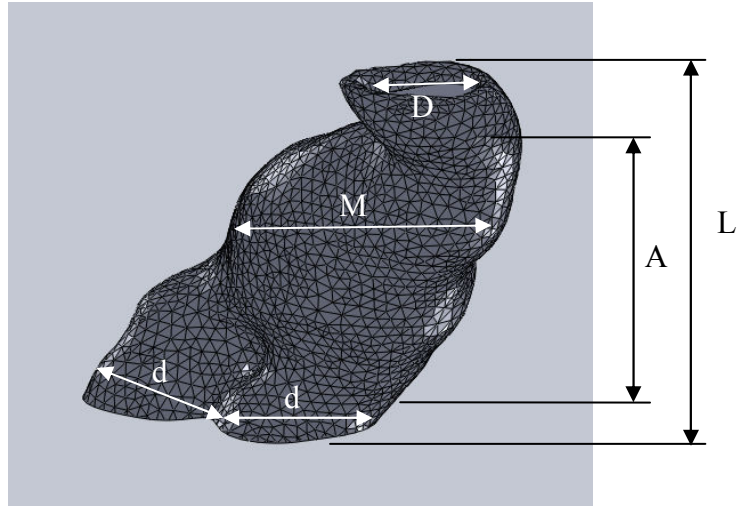


Figure 3.6: Model of abdominal aortic aneurysm constructed.

Table 3.1: Geometry specification of abdominal aortic aneurysm.

D (mm)	M (mm)	d (mm)	M/D (mm)	A (mm)	L (mm)
38	77.65	32	2.02	64.32	102.71

3.5 Governing Equations

In these simulations, Computational Fluid Dynamic software called Engineering Fluid Dynamic (EFD) was used. Both velocity inlet and pressure outlet are computed to solve the continuity and Navier-Stokes equations. Hence, the physical laws describing the problem of AAA are the conservation of mass and the conservation of momentum. For such a fluid, the continuity and Navier–Stokes equations are as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\rho \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = -\frac{\partial P}{\partial x_j} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i \quad (2)$$

Where u_i = velocity in the i^{th} direction, P = Pressure, f_i = Body force, ρ =Density, μ_i =Viscosity and δ_{ij} = Kronecker delta. The shear stress, τ at the wall of aneurysm is calculated based on a function of velocity gradient only:

$$\tau = \mu \frac{\partial u}{\partial y} \quad (3)$$

Where $\partial u/\partial y$ is the velocity gradient along the aneurismal wall taking into considerations the fluid viscosity. Therefore, the simple viscous fluids considered with linear relationship.

The solver solves the governing equations with the finite volume method on a spatially rectangular computational mesh designed in the Cartesian coordinate system with the planes orthogonal to its axes and refined locally at the solid and fluid interface. Additional refining was done for specified blood regions, at the arterial and aneurysm surfaces during calculation. Values of all the physical variables are stored at the mesh cell centers and due to the Finite Volume method, the governing equations are discretised in a conservative form and the spatial derivatives are approximated with implicit difference operators of second-order accuracy. The time derivatives are approximated with an implicit first-order Euler scheme.

3.6 Initial and Boundary Conditions

The initial and boundary conditions for the flow field must be specified before running the simulation to get reliable result. In this study, boundary conditions are specified on the inlet and outlets of the aneurysm which is in contact with the fluid.

In this simulation, the inlet flow was considered fully developed parabolic flow, zero radial velocity at the inlet, no slip applied at the wall and zero velocity gradients at the outlet. The inlet boundary conditions setting were pulsatile velocity for resting and exercise condition which are shown in Figure 3.7 whilst the outlet

boundary condition setting were static pressure for time dependent for normal (NBP) and high blood pressure (HBP) which is shown in Figure 3.8.

For finite element analysis (FEA) of the aneurysm, both proximal and distal ends of the aneurysm were fixed.

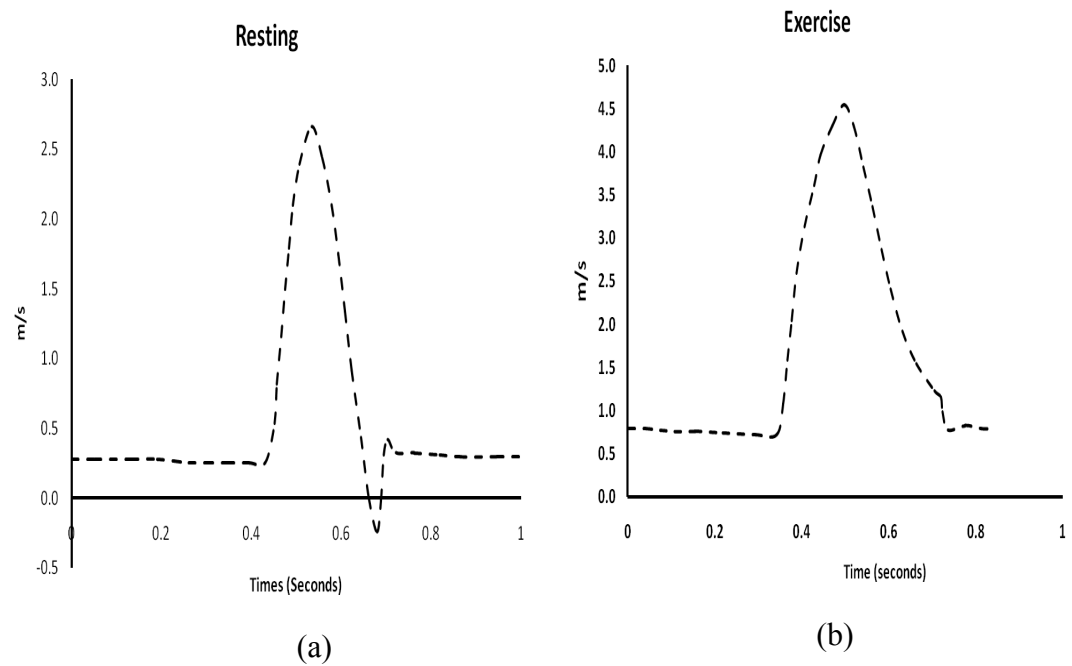


Figure 3.7: (a) Resting and (b) Exercise conditions waveforms (Egelhoff et al., 1999).

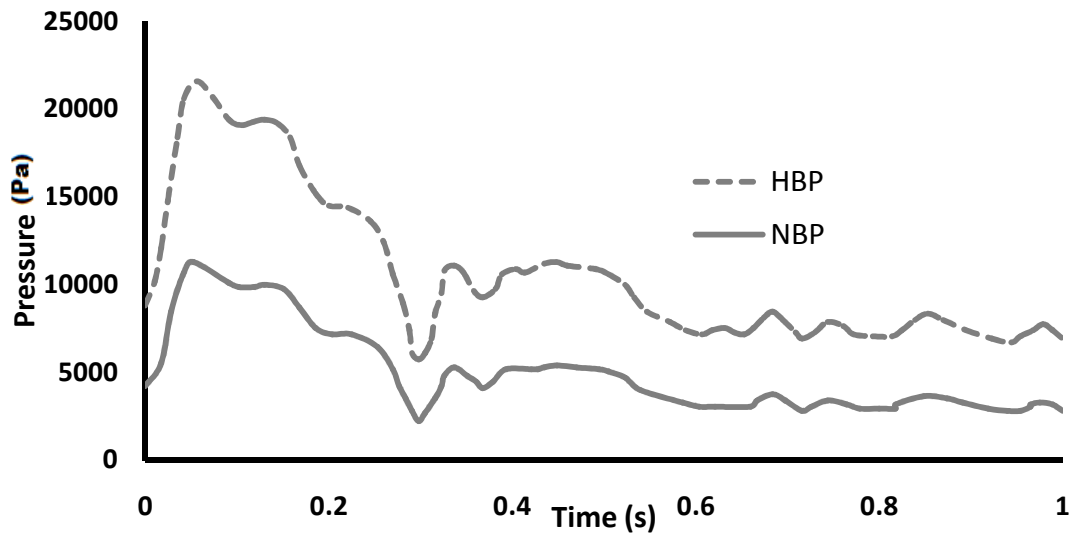
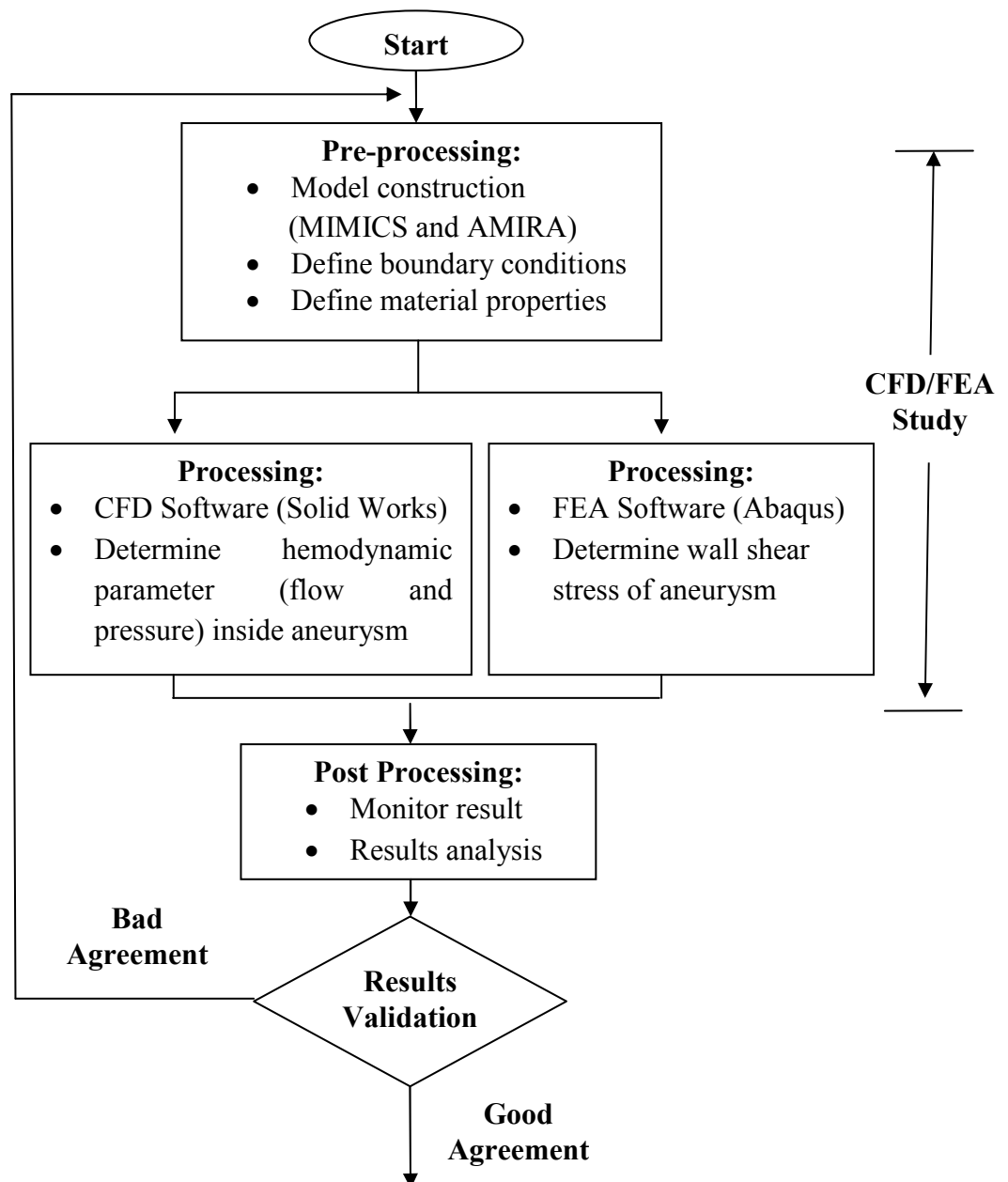


Figure 3.8: Pressure waveforms for HBP and NBP (Tayfun et al., 2008).

3.7 Project Methodology

In general, the step by step procedure to execute the project involving pre-processing, processing and post-processing is simplified in Figure 3.9.



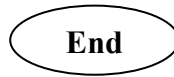


Figure 3.9: Project methodology flow chart.

3.8 Experimental Subject Consideration

In this study, subjects which are taken into consideration is divided into two groups which are HBP and NBP and tested for two physical conditions which are exercise and resting as shown in Figure 4.0.

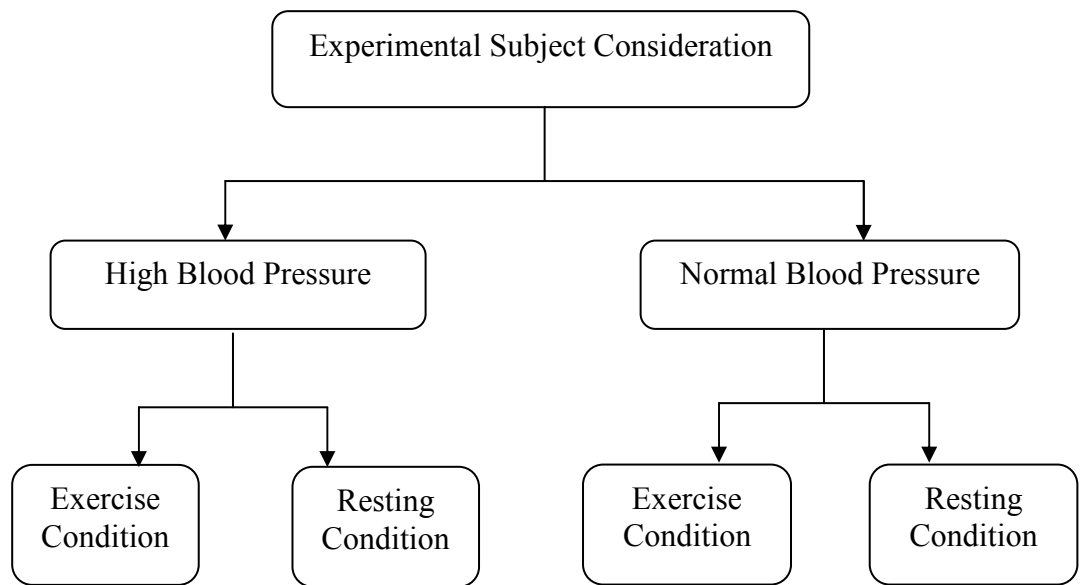


Figure 4.0: Experimental subject consideration.

CHAPTER IV

RESULTS & ANALYSIS

4.0 Introduction

This section will show and briefly explain the results of the current study. It has been divided into three main sections which were flow distribution, pressure distribution and wall shear stress of abdominal aortic aneurysm. They were intensely described in terms of exercise and resting condition for both normal and high blood pressure.

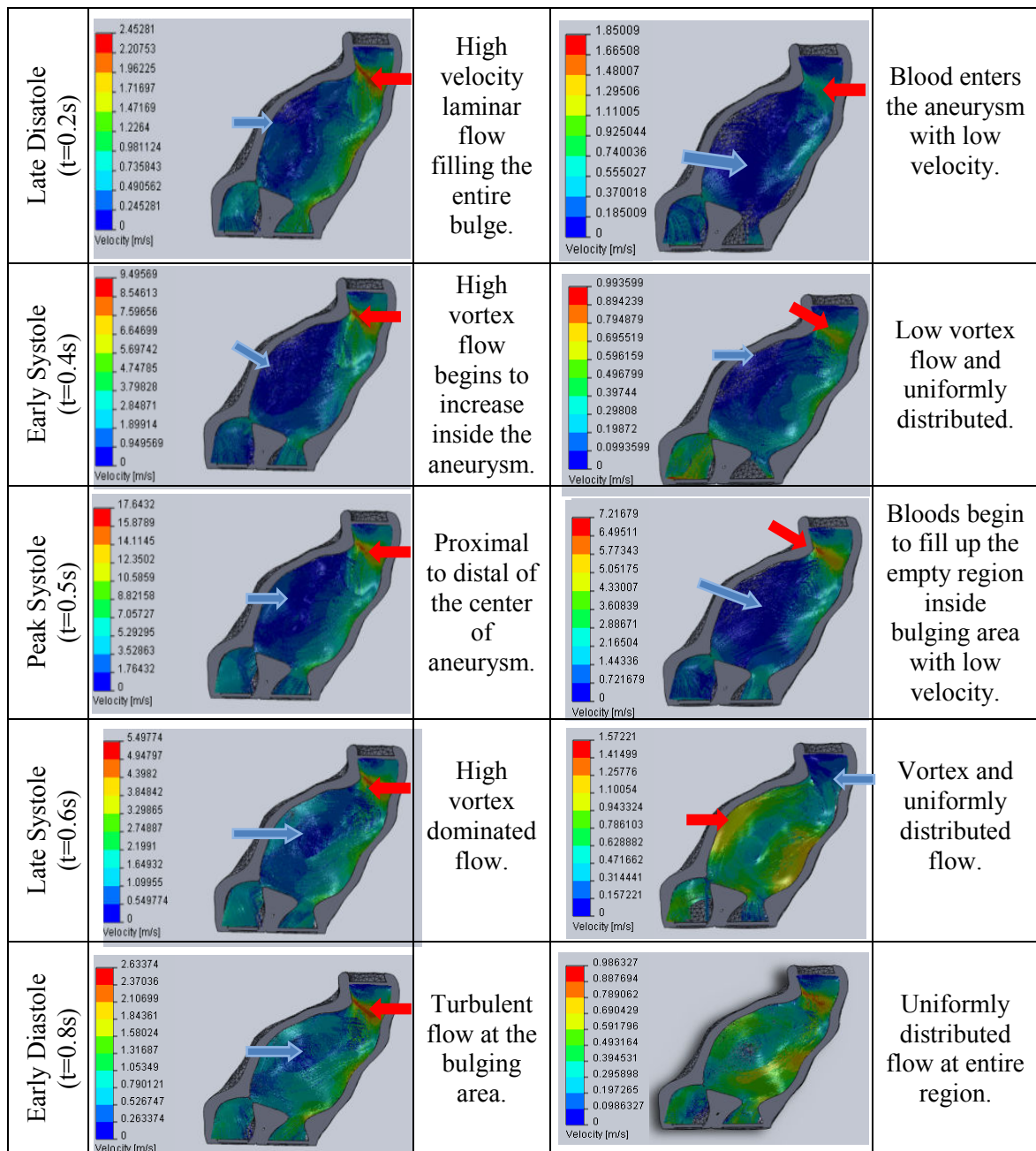
4.1 Flow Distribution

In order to have a clear picture of the phenomena that occur inside the aneurysm for flow distribution, results of flow visualisation are analysed for five difference periodic time which are late diastole (0.2s), early systole (0.4s), peak systole (0.5s), late systole (0.6s) and early diastole (0.8s).

4.1.1 Exercise Condition

Figure 4.1 mainly revealed the comparison of blood flow distribution between HBP and NBP during exercise noted as HBPE and NBPE respectively. It is observed that blood enters the inlet drastically for HBPE during late diastole (0.2s) compare to NBPE which crucially affect the neck region. During exercise for high and normal blood pressure, the blood flow enters inlet at about 2.45m/s and 0.55m/s respectively. At late diastole to peak systole (0.2-0.5s), the high flow vortex from the neck begins to take over the whole aneurysm and the value is growing for HBPE whilst for NBPE, the blood just begun to fill up the empty region inside bulging area. Results indicate that at the peak systole, highest velocity detected around the neck which is around 15.8 m/s for HBPE while 7.217 m/s for NBPE. When it reached the late systole to early diastole, HBPE showed great turbulent flow and vortex formation while NBPE have the same effect but with uniform flow distribution.

Phase	High Blood Pressure During Exercise (HBPE)	Normal Blood Pressure During Exercise (NBPE)
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 High Velocity Region
 Low Velocity Region

Figure 4.1: Comparison of flow pattern between high and normal blood pressure during exercise at different periodic time.

4.1.2 Resting Condition

For resting condition, results depicted that high blood pressure has greater and rapid flow changes over normal blood pressure at each phase as shown in Figure 4.2. Based on the results obtained for high blood and normal blood during resting, at late diastole ($t=0.2s$), the blood enters the inlet in high velocity focusing around the neck area at around 0.62 m/s and 0.53m/s respectively. Form early to peak systole (0.4s – 0.5s), highly vortex flow begins to dominate the whole bulging area for HBPR whilst low velocity flow at one side of the aneurysm region is observed for NBPR. During late systole (0.6s), results showed highly vortex formation around the aneurysm wall for both cases. At early diastole (0.8s), both cases have almost uniform turbulent flow but HBPR showed slightly greater value of velocity over NBPR.

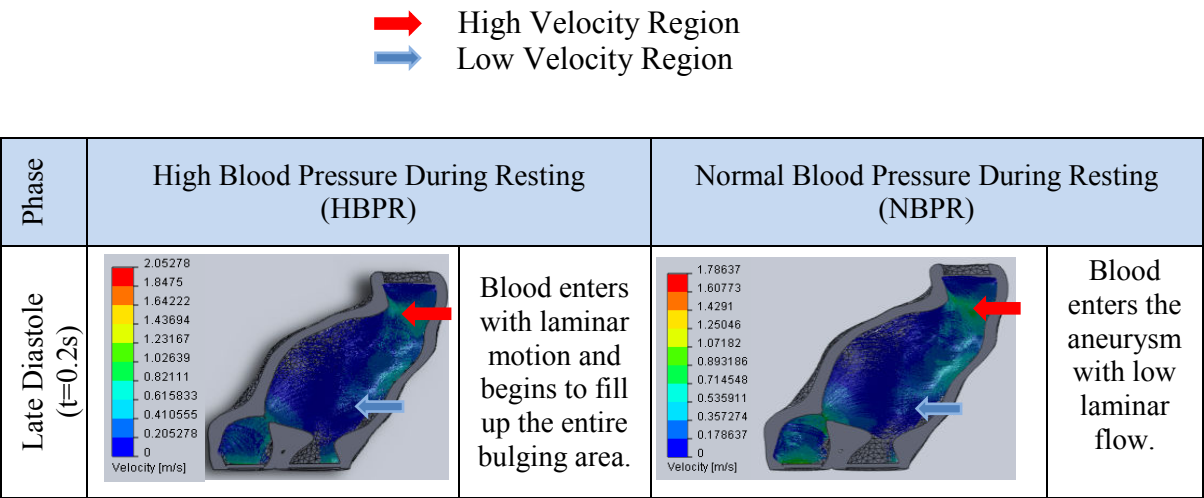


Figure 4.2: Comparison of flow pattern between high and normal blood pressure during resting condition at diffent periodic time.

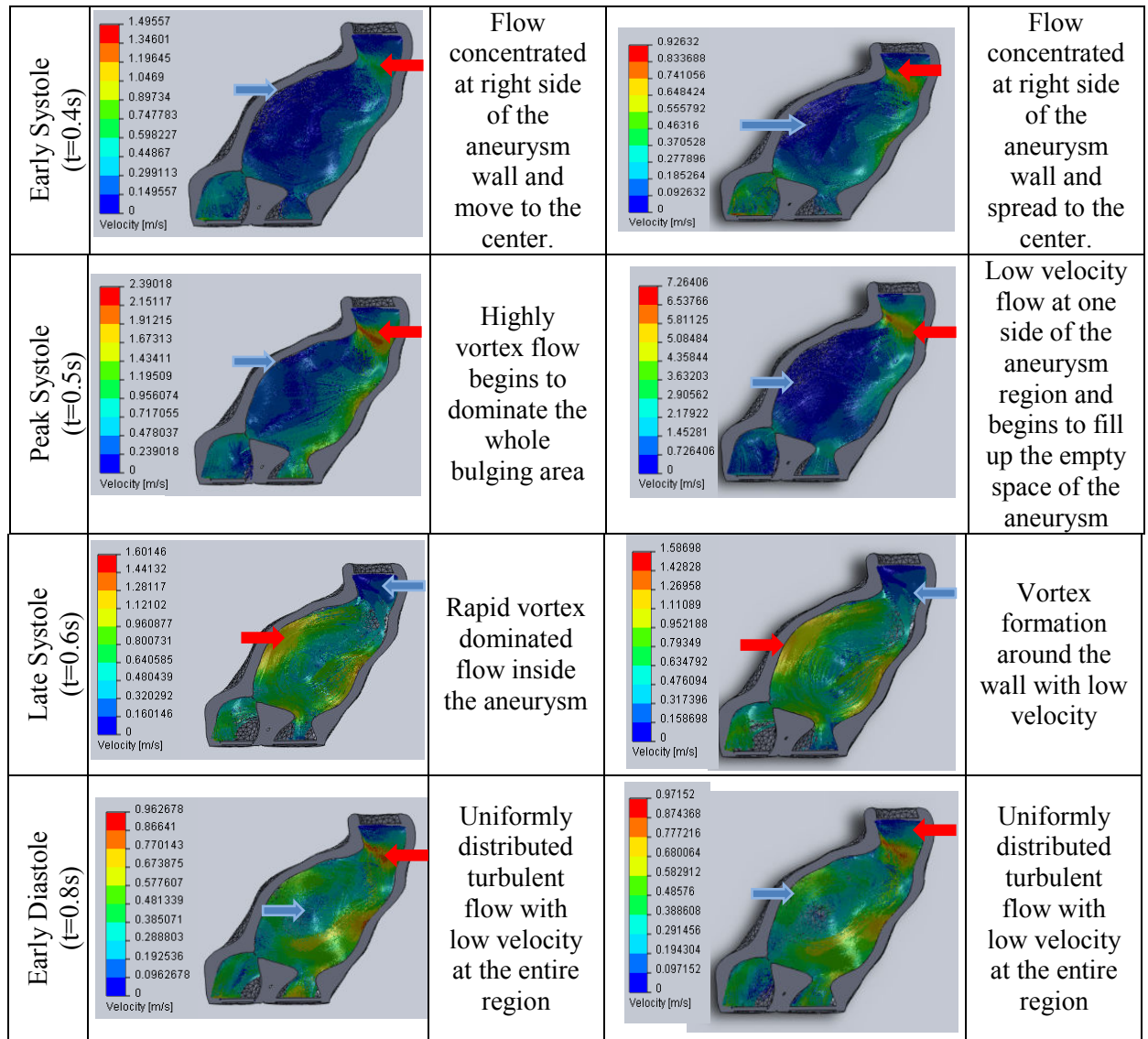


Figure 4.2,continued.

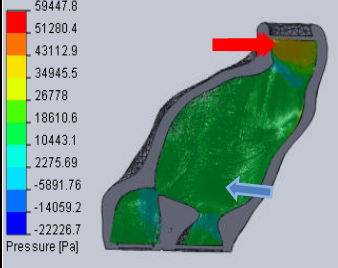
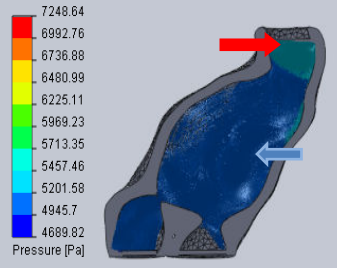
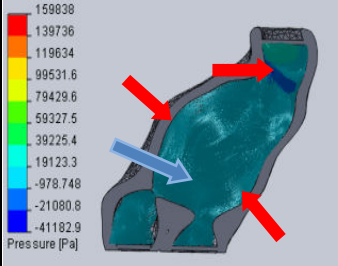
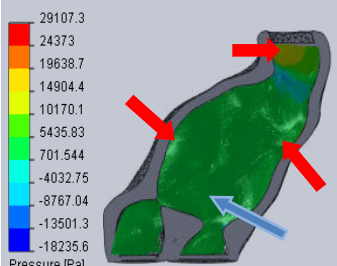
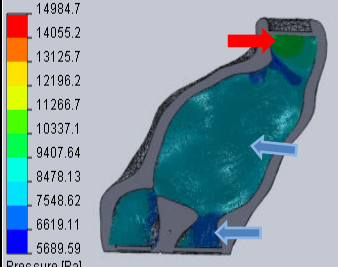

4.2 Pressure Distribution

The simulation results for pressure distribution for four experimented conditions that is HBP and NBP at exercise and resting condition are intensely

described in this section. The results are analysed for three different stage of time namely early, mid and late stage.

4.2.1 Exercise Condition

Figure 4.3 indicates pressure distribution of HBP and NBP during exercise for three stage of time group namely early, mid and late stage. Executing simulation for exercise condition result in increment of pressure distribution inside the bulging area during the early stage (0-0.4s) as the blood begins to fill up the empty space inside the aneurysm for both cases. The neck area obviously shows great pressure for the entire periodic time due to high velocity at that particular area at all time. During the mid stage (0.5-0.6s), simulation results depict the highest pressure distribution of all periodic stage specifically at aneurysm wall region which is around 16000 Pa for HBPE and 5500 Pa for NBPE. At this time frame, the pressure decreases from distal to proximal of the bulging region. It is coherent with the active blood flow pattern where at late systole (0.5s) shows highly vortex flow. At the final stage (0.7-1s) of the periodic time indicates HBPE and NBPE shows approximately half of pressure value as in mid stage in the bulging area at around 7500 Pa and 3000 Pa respectively due to turbulent flow generated. In all stages, it is identified that HBPE shows greater pressure value compare to NBPE due to active flow behaviour.

Stage	High Blood Pressure Exercise (HBPE)		Normal Blood Pressure Exercise (NBPE)	
Early (0-0.4s)		Bloods enters the aneurysm at high pressure and rapidly fill up the entire aneurysm region.		Blood enters the aneurysm at low pressure than slowly fill up the bulging area.
Mid (0.5-0.6s)		The pressure increased inside the bulging area due to vortex flow.		The pressure inside the bulging area increased but lower than HBPE case.
Late (0.7-1s)		Pressure decreased at almost entire region but remain high at the inlet		Pressure decreased at almost entire region.

 High Pressure Region
 Low Pressure Region

Figure 4.3: Pressure distribution of HPB and NBP during exercise

4.2.2 Resting Condition

Figure 4.4 reveals results of pressure distribution for HBP and NBP for resting condition represents as HBPR and NBPR respectively. Based on the results obtained, both HBPR and NBPR showed almost the same result pressure pattern as in exercise conditions but significantly differ in term of pressure value. At the early

stage (0-0.4s), the pressure concentrated at the inlet region for both cases with HBPR having slightly greater pressure over NBPR at 10800 Pa and 5100 Pa respectively. At the mid stage (0.5-0.6s), pressure at HBPR increased rapidly at wall and outlet region with maximum value approximately 8200 Pa while NBPR showed pressure increment as well but focused mainly at the outlet region with maximum pressure around 5400 Pa. At the final stage (0.7-1s), the pressure decreases for both cases. The neck region obviously showed greater pressure effect at all time.

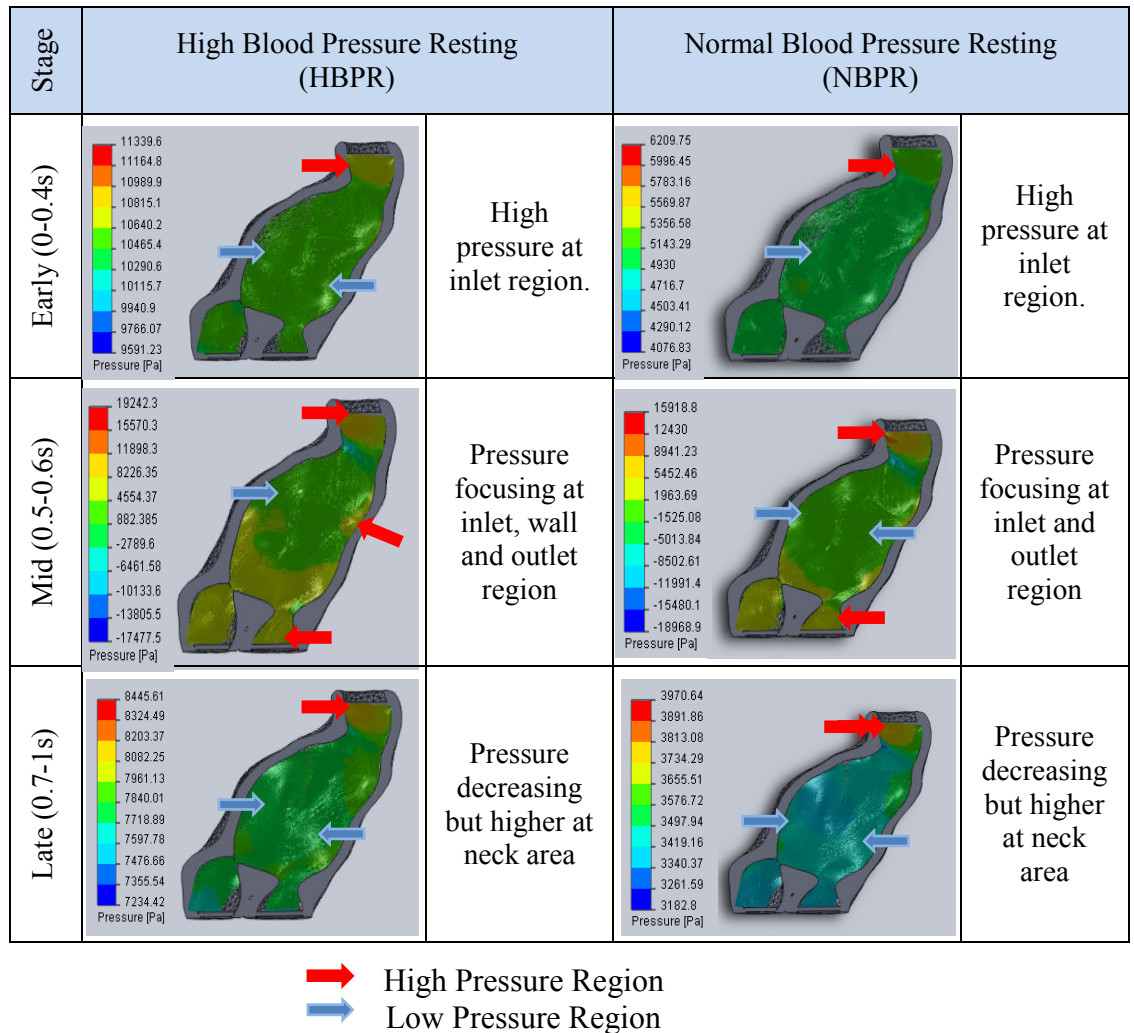


Figure 4.4: Pressure distribution of HPB and NBP during Resting

4.3 Wall Shear Stress Distribution

Figure 4.5 reveals mainly simulation results of wall shear stress (WSS) pertain to high blood pressure and normal blood pressure for different period of time. Based on the results, the stress begins to increase slowly and reached its peak at the late stage of the periodic time. At early diastole (0.8s), the WSS results for HBP and NBP showed highly stress focused region that may rupture represented in red colour at approximately 9046 Pa and 3676 Pa respectively. It is noticed that high WSS mainly spots on the center of the bulging area and also at the outlet region. The WSS distribution in the aneurysm is possibly influenced by stress around the bulging area due to vortex formation and turbulent flow inside the aneurysm. Basically, both high blood and normal blood pressure showed similar WSS distribution patterns aiming at the same spot. However, the pressure value for HBP case showed 2.46 times greater impact than NBP case.

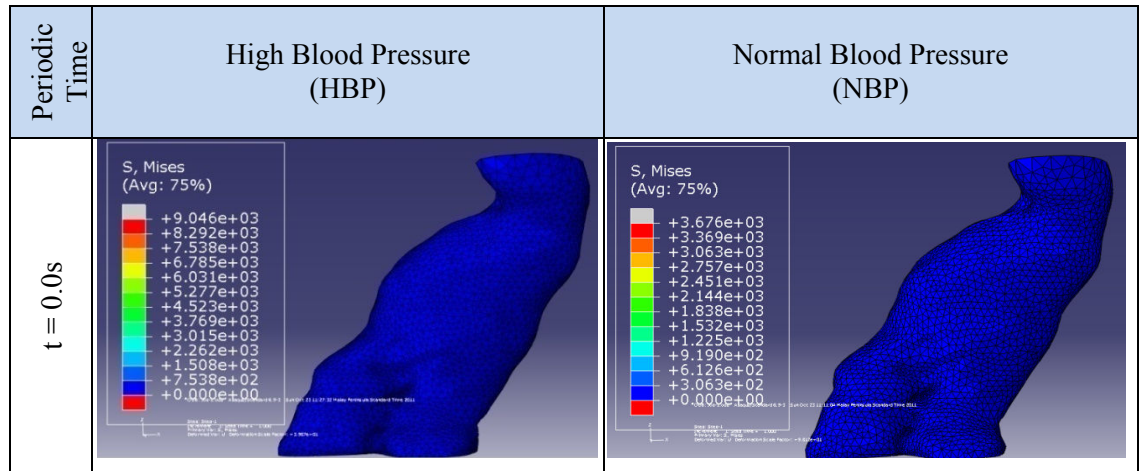
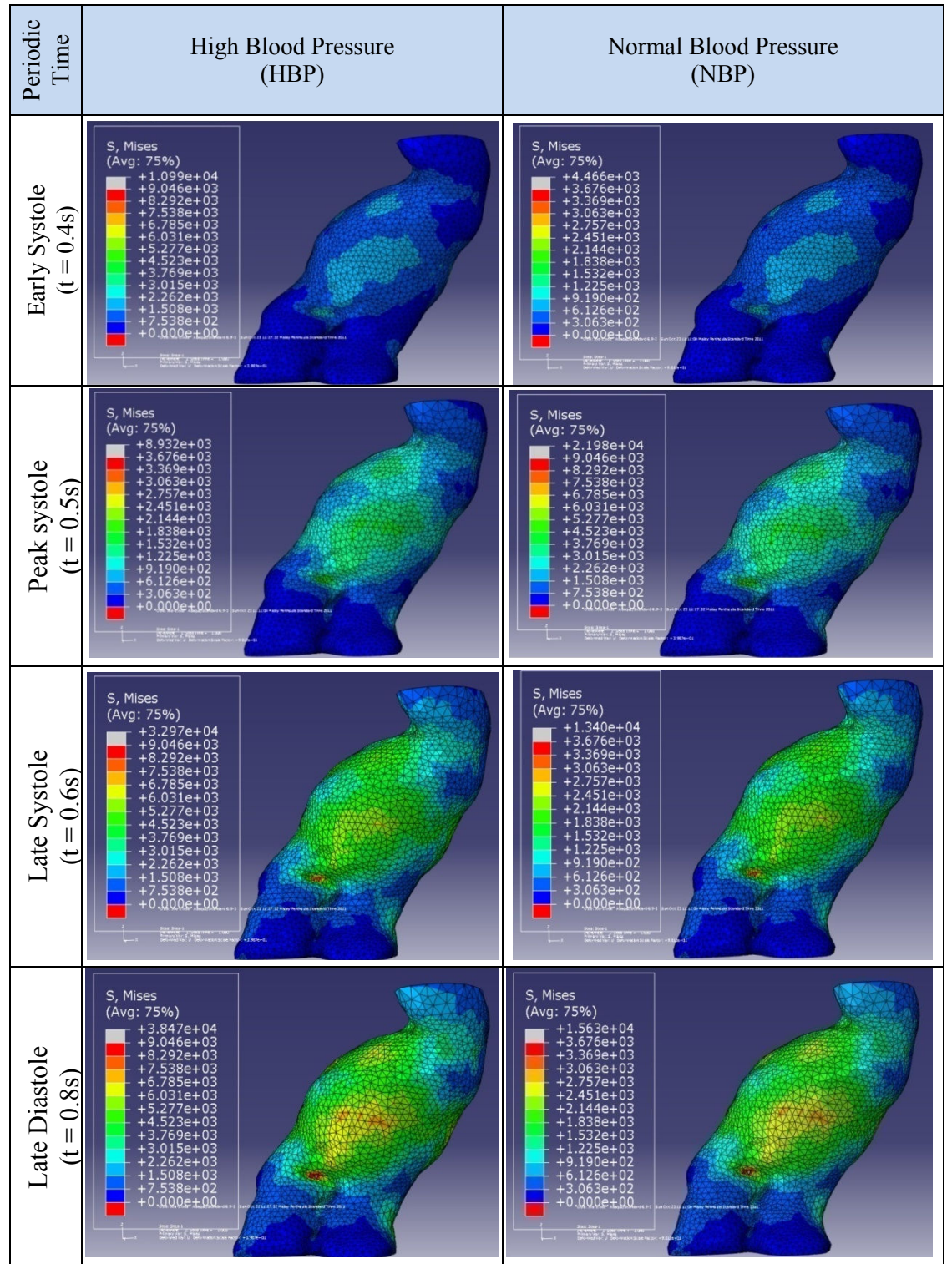


Figure 4.5: Comparison of WSS distribution between high and normal blood pressure for different periodic time.

Figure 4.5,continued.



CHAPTER V

DISCUSSIONS

5.0 Introduction

This section will describe the relationship of hemodynamic factors such as blood flow, pressure and wall shear stress for NBP and HBP by referring to results in Chapter IV.

5.1 Interaction between Blood Flow, Pressure and Wall Shear Stress

In general, the interaction between the blood flow, pressure and wall shear stress at the aneurysm wall between HBP and NBP is illustrated in Figure 4.6. The diagram intensely shows that blood flow velocity have an effect on the aneurysm wall for both high blood and normal blood case.

The similarity for both cases is that the pressure concentrated at the same area but differs in terms of pressure value whereby HBP has a greater pressure value compare to NBP. Theoretically, pressure is directly proportional to velocity. Therefore, as the blood flow in the same region increased, it will lead to increment of the pressure due to vortex formation inside the aneurysm region. This phenomena

will causes the overall flow inside the aneurysm region to experience change in the velocity that will lead to unstable blood flow.

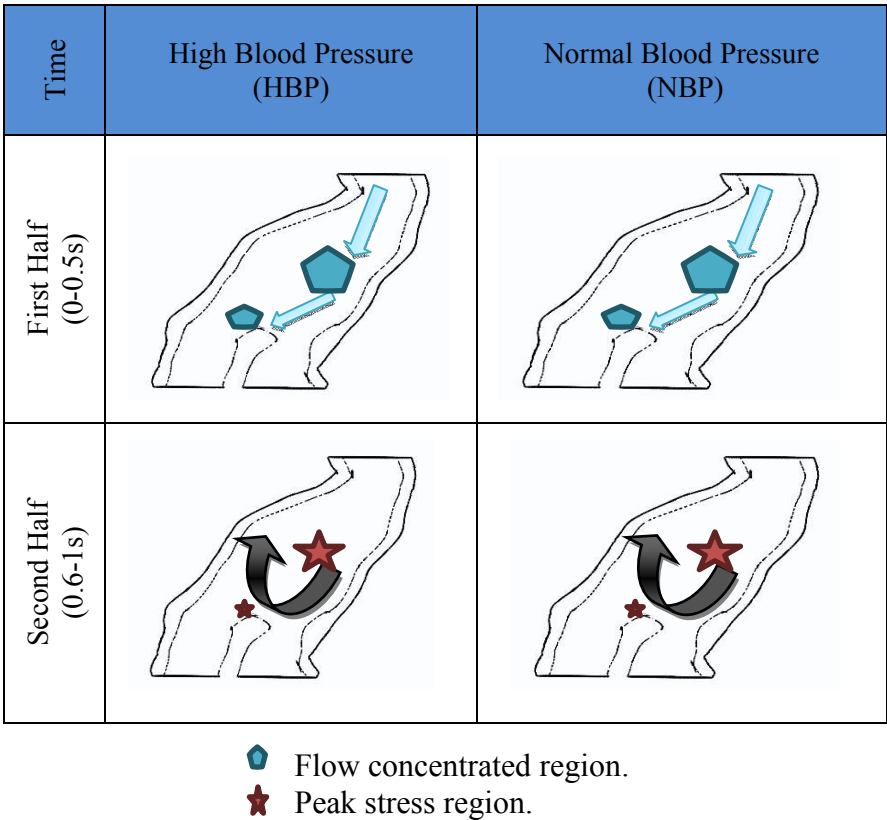


Figure 4.6: Relationship of blood flow, pressure and wall shear stress for high and normal blood pressure at first and second half of periodic time.

On the other hand, WSS shows increment of stress in the early stage and reached its peak at the late stage of the periodic time. After peak systole phase (0.5s), WSS value will not decrease but becomes higher even the blood velocity does. This is due to vortex domination and turbulence flow at late stage (0.6s-1s) which results from hasty flow pattern at first half. At this point, the artery is likely to swell more and reasonable to rupture. These results is tally with the research

conducted by Khalil M. Khanaffer (2007) which found that the turbulence induced by sudden expansion of the flow stream generates higher fluid shear stresses on the aneurysmal wall and causing for further wall dilation that will eventually result in greater turbulence for aneurysmal growth.

Technically, HBP during exercise (HBPE) exhibit rapid blood flow and greater pressure pulse over NBP case. It is based on flow waveform during exercise and resting (Egelhoff et al., 1999) and pressure waveform of NBP and HBP (Tayfun et al., 2008). Simulating the hemodynamic factor of the aneurysm for NBPE, HBPE, NBPR and HBPR has shown that hypertensive blood pressure has much more potential for aneurysm growth. In addition, simulating at exercise condition multiplies the effect in the aneurysm for both HBP and NBP. Thus, there is high percentage of aneurysm for hypertensive blood pressure during exercise that is considerably to rupture.

CHAPTER VI

CONCLUSIONS

Research shows that there are few factors that affect the pressure in the aneurysm region for both high blood and normal blood pressure at exercise and resting state. The blood flow patterns for each phase highly cause an impact in the aneurysm. The highly vortex flow which started at peak systole (0.5s) and increase at the continuity phase shows greater effect of pressure and wall shear stress at the aneurysm. At late stage (0.8-1s), as the flow becomes turbulent, it creates uniform and low pressure distribution inside the aneurysm. Although the blood velocity decreases, the WSS does not because of the vortex effect. In addition, WSS value observed shows increment at the end of periodic time and indicates areas that is highly prone to rupture.

From the research findings, for blood flow distribution, HBP has rapid flow changes and causes great vortex formation inside the aneurysm compared to NBP which has likely uniform and stable flow. During exercise and resting condition tested, it shows that HBP has significant flow changes compare to NBP. Although, the pressure and WSS for exercise and resting condition shows not much difference in term of pressure distribution, it is widely differ in term of its quantitative value where HBP showed 2.46 times greater impact than NBP.

As summary, the blood flow does affect the pressure distribution and aneurysm expansion for both high and normal blood pressure. However, in every case experimented for hemodynamic factors, hypertensive blood pressure during exercise exhibited greater hemodynamic effect in the aneurysm region due to active blood flow.

The next step of this research will be the expansion of the analysis in a variety of ways, such as the analyzing for other aneurysm which occur at different part of the body (i.e. thoracic and brain), modelling different types of aneurysm (i.e. pseudoaneury and saccular) and analyzing different types of materials (i.e. metal and nitinol) and design (i.e. diamond-shape and tubular rings with bridging links) as an alternative for endovascular aneurysm repair (EVAR).

At the end of the day, it is hope that the findings of this research can be used as a reference for the biomechanics community for their future implementations, resources and knowledge for a better prediction of rupture analysis.

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